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Effects of vegetation control on *Eucalyptus grandis* x *E. camaldulensis* volume and economics

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A trial was initiated in 1990 to determine the impact of early vegetation competition on the growth of a *Eucalyptus grandis* x *E. camaldulensis* hybrid (GC304) at a subtropical site in KwaZulu-Natal, South Africa. Treatments included a non-weeded control, a manually weeded treatment, a chemically weeded treatment, a 1.2m row and 1.2m inter-row weeding, a 0.5m radius ring weeding, a complete weeding except for a 0.5m radius ring around the tree, and the use of two legume cover-crops, *Mucuna puriens* (L.) DC. and *Vigna unguiculata* (L.) Walp. Growth responses to treatments and economic profit were assessed when the trial was felled at seven years of age. Initial growth benefits (first detected from 60 days after planting) were maintained until the trial was felled. The manually weeded treatment produced 62% more merchantable timber, at an increased profit of 30%, than the non-weeded control, thereby demonstrating the potential gains that can be obtained through vegetation control. The non-weeded control, inter-row weeding and the cover-crops experienced interspecific competition during tree establishment and yielded trees of similar height but smaller taper when compared with other treatments. This work shows that volume estimates, derived by using only top height as a predictor variable, may be problematic for non-weeded stands due to the adverse effect of tree suppression on taper and hence timber volume.

Introduction

In South Africa various *Eucalyptus* species are grown over short rotations, ranging from six to 12 years. To meet the increasing demand for pulpwood from this source, forest companies will need to increase their timber output. This may be done either by increasing the amount of timber attainable from the existing land-base, or through the acquisition of additional land (Brown and Hillis 1984, Kimmins 1994). Present and future land-use policies are likely to restrict the conversion of non-afforested land to plantations. Improvements in timber yield from an existing land-base can be achieved by different means, some of which include site-species matching, tree breeding, clonal propagation, the use of interspecific hybrids, and through appropriate silvicultural practices. There are many examples where the silvicultural practices of site preparation (Smith *et al*. 2001), fertilisation (Du Toit *et al*. 2001) and spacing (Bredenkamp 1987) have resulted in increased eucalypt growth and thus final yield. Although a large body of literature deals with short- and long-term impacts of vegetation control on pines (Glover *et al*. 1989, Haywood and Tiarks 1990, Britt *et al*. 1991, Forest Nutrition Co-operative 2001, Little and Rolando 2001), and short-term impacts on eucalypts (Messina 1990, Wilkinson and Neilson 1990, Endo and Wright 1992, Little and Schumann 1996, Neilsen and Ringrose 2001), very little is available on the long-term impacts of vegetation control in eucalypts.

Although any improvement in final yield is important, this cannot be considered in isolation, as the profit to be gained from the management of vegetation during establishment is affected both directly and indirectly by the method of vegetation control (manual, chemical or cultural). Any improvement in yield therefore needs to be taken into consideration together with any weed control costs. The economic returns to be gained from enhanced tree performance through vegetation control have been demonstrated for pines (Nwonwu and Obiaga 1988, South *et al*. 1995), and in the short-term for eucalypts (Fremlin *et al*. 1999, George and Brennan 2002). Since vegetation control costs may be a major contributor to silvicultural costs, the degree of risk associated with such costs through to felling needs to be considered together with final volume, to determine the most profitable scenario. However, limited information is available regarding the relationship of vegetation control operations at establishment to final volume in eucalypt plantations.

In 1990, a field trial, using the hybrid combination of *Eucalyptus grandis* and *E. camaldulensis*, was implemented in Zululand, South Africa, to test various vegetation control scenarios. The trial was felled in 1997, and allowed for the determination of final timber volumes as influenced by vegetation control carried out during establishment. This information was combined with the vegetation control costs of the different treatments to determine the most cost-effective method of vegetation control. In addition, the relationship between stem form and site index, as influenced by vegetation control, is discussed.

Materials and Methods

The study was conducted near the coastal town of Mtunzini, KwaZulu-Natal (28°59'S and 31°42'E). The climate is classified as subtropical, with a mean annual rainfall and temperature of 1 144mm and 22°C, respectively. Although rain occurs throughout the year higher rainfall occurs during the summer months (October–March). The trial was located at an elevation of 45m asl on an east-facing slope. Soil parent material is of aeolian origin and is classified as an arenic lixisol or arenic kandiustult. The soil texture at the 0–20cm depth interval is sandy with low organic carbon (0.23%) and clay (9%) contents. Prior to the establishment of eucalypts, the site had previously been used for the production of sugarcane (*Saccharum* L. spp.). As a result of the aforementioned cropping practices, the predominant weed on the site was yellow nutsedge (*Cyperus esculentus* L.). However, with the conversion to eucalypts, the grass species *Panicum maximum* Jacq. became the dominant weed species. Initial weed development and tree growth responses to the treatments tested in this trial were reported by Little and Van Staden (2003).

A pre-plant spray with a non-selective herbicide (glyphosate) was undertaken prior to the establishment of a *Eucalyptus grandis* x *E. camaldulensis* clonal hybrid (GC304). The use of the clone imparted a high degree of uniformity to the stand. Trees were planted on 9 October 1990 at an inter-row and intra-row spacing of 3m and 2.5m respectively, resulting in a stocking rate of 1 333 stems ha^{-1}. Each tree was fertilised at planting with 60g limestone ammonium nitrate (LAN) (28% N), applied in a 0.2m diameter ring around each tree. Nine treatments, replicated four times, were imposed on the stand. Each treatment plot consisted of 30 trees (5 rows x 6 trees in each row) with the inner net plot of 12 trees being measured (3 rows x 4 trees in each row).

Nine treatments (Table 1) were first imposed on 22 October 1990, with the non-weeded control receiving no further weed control. The weed free (manual), row weeding, inter-row weeding, ring weeding and complete weeding except ring (no ring weeding) treatments were kept manually weeded in their respective zones with the use of hoes. Initial weed control for the chemically weeded treatment was carried out with the use of glyphosate sprayed at 4l ha^{-1} through knapsack sprayers. Care was taken to protect the trees with the use of inverted plastic cones. Subsequent chemical weeding operations were carried out on the inter-row with a hand-drawn shielded spray boom. The cover-crops of cowpea (*Vigna unguiculata* (L.) Walp.) and velvet bean (*Mucuna pruriens* (L.) DC.) were planted in double rows, 1m from the tree rows. The cowpea seeds were planted at a spacing of 0.1m and the velvet beans at 0.2m.

Table 1: List of weeding and cover-cropping treatments

Number	Treatment	Method/species
1	Non-weeded control	None
2	Weed free	Manual
3	Weed free	Chemical
4	Inter-row weeding (1.2m width)	Manual
5	Ring weeding (0.5m radius)	Manual
6	Complete weeding except ring[1] (0.5m radius)	Manual
7	Row weeding (1.2m width)	Manual
8	Cover-crop with weeding to establish	Cowpea
9	Cover-crop with weeding to establish	Velvet bean

[1] This treatment is described in the text and tables as 'no ring weeding'

The cover-crops were fertilised at planting with 10g 2:3:2 (N:P:K) + 0.5% Zn m^{-1} row. The cover-crops were manually weeded on two occasions until a full plant cover had been established, thus reducing the need for further weed control. Weed control operations were carried out on a monthly basis in all the manually weeded treatments, except the non-weeded control and the cover-cropping treatments. This continued until canopy closure, after which the limited light available for growth restricted further weed development.

Prior to felling, the over-bark diameters at breast height (Dbh_{ob}) were measured and marked on all the trees. The trees were felled as close as possible to the ground (0.05m stump height). Once felled, the height to the top of each tree (H_{top}) and height to a minimum over-bark stem diameter of 0.07m ($H_{0.07}$) were measured. Under-bark diameter measurements were taken at breast height (Dbh_{ub}) as well as at 2.4m intervals, from the base of the stem up to and including the diameter at $H_{0.07}$.

For each 2.4m section, the under-bark volume (V_{sec}) was calculated using the formula for a truncated cone, whereas the volume of the last section (V_{last}) of the tree (from $H_{0.07}$ to the top of the tree H_{top}) was calculated using the formula for a cone (Cailliez 1980). The total volume for each individual tree (V_{tot}) was then calculated as the sum of the volumes of the tree sections. From this the total volume per hectare (V_{totha}) was calculated, using the stocking obtained for the respective treatments. Merchantable volume for each individual tree (V_m) and the total merchantable volume per hectare (V_{mha}) were calculated similarly, excluding the volume from the last section (V_{last}).

To give an indication of the decrease in diameter with tree height, the taper of individual trees was calculated (Clarke *et al*. 1997) as:

$$\text{Taper} = \frac{d_{base} - d_{0.07}}{H_{0.07}} \qquad (1)$$

where d_{base} is the under-bark diameter of the tree at stump height, $d_{0.07}$ is the under-bark diameter corresponding to an over-bark diameter of 0.07m, and $H_{0.07}$ is the height to a minimum over-bark diameter of 0.07m.

Before comparisons between individual treatment means were made, an overall F-test was carried out. This provided an overall test of the significance of the differences observed between all the treatment means in the experiment (Mead and Curnow 1983). Only if the F-value was significant were treatment differences further investigated, using least significant differences (LSDs). Unless otherwise stipulated, comparisons between the tree variates were analysed as a randomised complete block design, with the use of GenStat® for Windows™ (Lane and Payne 1996). In addition, Bartlett's test (Snedecor and Cochran 1956) was used to test the assumption of homogeneity of variance in order for a valid analysis of variance to be performed. Only tree height was significantly different, indicating the presence of heterogenous variance. The Fisher-Behrens test (Campbell 1974), which uses separate variance estimates for the samples, was then used to determine differences between the means for the tree heights.

To calculate weed control expenditure, the number of weed control events and estimated costs for the different weeding regimes were determined. All treatments received a pre-plant glyphosate spray, at a cost of US\$30.37 ha^{-1}, and this was incorporated in the total establishment weed control costs. The estimated weeding costs were adjusted to account for compound interest, using actual interest rates (based on Mondi Forests' Afforestation Accountancy Policy) over the period October 1991 to October 1997. After determining the price that would have been received for the timber in 1997 (US\$20.9 m^{-3}), the costs of establishment weed control were deducted. No other establishment costs (marking, pitting, planting or fertilisation) have been deducted, as these were common to all treatments.

Results and Discussion

Tree volume and tree form at felling

Initial tree growth responses to the treatments tested in this trial were reported by Little and Van Staden (2003). The type, duration and proximity of competing vegetation during establishment had a lasting effect on tree performance. Significant differences between the treatment means for all variates measured remained for the duration of the trial, with the non-weeded control and weed free (manual) treatment producing the worst and best growth, respectively (Table 2). As no competitive vegetation was present on the site during the post-establishment phase, it is assumed that it was the initial treatment responses that affected tree growth later in the rotation. Tree growth during the latter stages of the trial was, therefore, affected by intraspecific competition for the resources of the site. As the resources available for tree growth on any given site will be finite, they will limit tree growth as the stand develops. Diameter at breast height and height measurements were significantly different when the trees were felled, as were volume and merchantable volume per hectare (Tables 2 and 3). In terms of the mean tree volume, this translated into a 74% gain, highlighting the large potential obtainable through vegetation management, especially for eucalypts grown on a short pulp-wood rotation.

Being a derived value, the merchantable volume per hectare is influenced by tree height and stem area, as well as the stocking. The effect of top height does not have as much influence on volume as that of diameter at breast height. Relative to the manually weeded treatment, only the heights of trees in the non-weeded control, the inter-row weeding and the velvet bean cover-crop were significantly different ($P < 0.05$) (Table 2). In comparison, all the treatments were significantly different to the manually weeded trees, for diameter at breast height. There was a 25% reduction in diameter at breast height between trees in the manually weeded treatment and the non-weeded control, and only a 16% reduction for height (Table 2). This may be due to intraspecific competition among the trees for light, where height growth occurs at the expense of diameter growth, especially in those treatments where initial suppression occurred.

Cannell and Grace (1993) indicate that one of the ways a plant may respond to shading is by an increase in extension of growth through an increase in their allocation of assimilates to the shoot. As tree height in this trial was not measured between Day 603 after planting until the trees were felled, the resource allocation in terms of height and diameter growth over time could not be quantified from the data available. However, height and diameter data available from two mensuration trials on *Eucalyptus grandis* suggest that under weed free conditions, diameter growth is favoured over that of height growth at two years of age. In the first trial, situated in Zululand near Kwambonambi, data from the treatment that had a stocking of 1 300 stems ha^{-1} showed the diameter at two years of age to be already 60.4% of the diameter measured at seven years of age, whereas the height was only 47.7% of the height at seven years of age (Coetzee *et al*. 1996). Similarly, the second trial, situated in the KwaZulu-Natal Midlands at Kia-Ora, showed the diameter and height expressed as a percentage of the final diameter and height to be 63% and 49.5% respectively (Coetzee and Naiker 1998). If one assumes that a similar pattern of growth applies to *Eucalyptus* hybrids grown under weed free conditions in Zululand, then the trees not competing for light would have a larger taper than those that are.

In this vegetation control trial, most of the trees were in the 18–20m height class, except for the manually weeded treatment, where the majority of the trees were in the 20–22m height class. In direct contrast, there was much greater variation in the diameter-at-breast-height treatment distributions both within and between treatments. The relationship between height and diameter at breast height was assessed using Equation (1). The use of this equation gives an indication of the decrease in diameter with increasing tree height. The treatment with the smallest taper was the non-weeded control, with the greatest being the manually weeded treatment (Table 2). In other words, the trees in the non-weeded plots were taller relative to their diameter than trees from the manually weeded treatment. That there was no significant difference in taper between trees in the non-weeded control, the inter-row weeding treatment and the cowpea and velvet bean cover-crop treatments, supports the fact that growth in terms of height was partially in response to competition for light. This is especially the case in those treatments where initial tree growth was delayed, due to interspecific competition.

Table 2: Treatment means calculated by using either all the trees per treatment plot or the largest three trees per treatment plot in a weeding and cover-cropping trial situated in Zululand, South Africa

	Tree height		Diameter at breast height		Volume			Taper	
	Mean tree height as determined by the:		Mean Dbh_{ob} as determined by the:		Mean volume per tree as determined by the:		Percentage of total volume accounted for by the top 25% performers	Mean taper per tree as determined by the:	
	Mean of all the trees[a]	Mean of the top 25% of the trees per plot[a]	Mean of all the trees[a]	Mean of the top 25% of the trees per plot[a]	Mean of all the trees[a]	Mean of the top 25% of the trees per plot[a]		Mean of all the trees	Mean of the top 25% of the trees per plot
Treatments	(m)	(m)	(cm)	(cm)	(m^3 $tree^{-1}$)	(m^3 $tree^{-1}$)	(%)	(cm m^{-1})	(cm m^{-1})
Weed-free (manual)	19.54	20.17	17.27	20.34	0.2004	0.2612	32.6	0.842	0.985
Weed-free (chemical)	18.82	20.12	15.37	18.68	0.1531	0.2136	34.9	0.746	0.888
	(3.68%)	(0.25%)	(11.00%)	(8.16%)	(23.60%)	(18.22%)			
No ring weeding	18.91	20.42	15.41	19.68	0.1602	0.2393	37.3	0.762	0.959
	(3.22%)	(–1.24%)	(10.77%)	(3.24%)	(20.06%)	(8.38%)			
Row weeding	18.78	20.14	15.30	19.48	0.1558	0.2432	39.0	0.754	0.920
	(3.89%)	(0.14%)	(11.41%)	(4.23%)	(22.26%)	(6.89%)			
Ring weeding	18.53	20.05	14.86	19.08	0.1542	0.2372	38.5	0.778	0.949
	(5.17%)	(0.59%)	(13.95%)	(6.19%)	(23.05%)	(9.19%)			
Cowpea	18.61	20.48	14.78	19.08	0.1444	0.2356	40.8	0.731	0.903
	(4.76%)	(–1.54%)	(14.42%)	(6.19%)	(27.94%)	(9.80%)			
Velvet bean	18.41	19.68	14.5	18.20	0.1382	0.2110	38.2	0.729	0.886
	(5.78%)	(2.43%)	(16.04%)	(10.52%)	(31.04%)	(19.22%)			
Inter-row weeding	17.45	20.59	13.83	19.96	0.1376	0.2565	46.6	0.722	0.943
	(10.69%)	(–2.08%)	(19.92%)	(1.87%)	(31.34%)	(1.80%)			
Non-weeded control	16.48	18.86	12.99	16.91	0.1152	0.1760	38.2	0.672	0.786
	(15.66%)	(6.49%)	(24.78%)	(16.86%)	(42.55%)	(32.62%)			
Mean	18.39	20.06	14.92	19.04	0.151	0.2304		0.748	0.913
SED	0.559	0.757	0.848	1.091	0.0158	0.0325		0.033	0.049
F-prob.	<0.001	0.493	<0.001	0.129	<0.001	0.282		<0.001	0.023
$LSD_{(0.05)}$	1.099	–	1.667	–	0.031	–		0.065	0.101

[a] The figures in brackets indicate the percentage reduction in height, Dbh_{ob} and volume respectively, relative to the manually weeded treatment

Table 3: Estimated effect of establishment weeding costs on final prices received for *Eucalyptus grandis* x *E. camaldulensis* timber in a weeding and cover-cropping trial situated in Zululand, South Africa

Type of weeding operation	Method	Cost of each operation in 1990/1 (US$ ha^{-1})	Number of weed control operations	Total weed control costs incurred during establishment (1990/1) (US$ ha^{-1})	Total establishment weed control costs adjusted for financial charges[a] (US$ ha^{-1})	Merchantable volume (m^3 ha^{-1})	US$ per volume (US$ m^{-3})	Price that would have been received for the timber at the 1997 price of US$20.9 m^{-3} (US$ ha^{-1})	Price of timber after deduction of establishment weeding costs (US$ ha^{-1})
Pre-plant spray		30	1						
Complete weeding	Manual	159	4	668	1 006	223.9	4.49	4 677	3 671
	Chemical using cones	64	2	159	239	191.4	1.25	3 998	3 759
Ring weeding (1m diameter)	Manual	17	4	100	151	196.1	0.77	4 096	3 945
Row weeding (1.2m)	Manual	53	4	243	366	185.6	1.97	3 877	3 511
Inter-row weeding (1.2m)	Manual	53	4	243	366	169.4	2.16	3 538	3 172
No ring weeding (1m diameter)	Manual	142	4	598	901	207.5	4.34	4 334	3 433
Cowpea cover-crop with	Seed + fertiliser + planting costs	34	1	330	497	158.1	3.14	3 302	2 805
weeding to establish	Manual	159 + 106	2						
Velvet bean cover-crop with	Seed + fertiliser + planting costs	34	1	330	497	160.6	3.10	3 355	2 858
weeding to establish	Manual	159 + 106	2						
Non-weeded control	–	–	–	30	46	137.8	0.33	2 878	2 833

[a] Interest capitalisation has been based on Mondi Forests' Afforestation Accountancy Policy using actual compound interest over the period October 1991–October 1997

The influence of competing vegetation on site index as determined by top height

The suitability of land for forestry plantations may be defined, in part, by a measure of 'site index' that infers potential productivity from tree height at a particular age (Bredenkamp 1993, Battaglia and Sands 1997). For example, a site index of 25 with five years as the reference age infers that the top height at age five years will be 25m. Site index curves are constructed so that the measured top height at any age provides an estimate of the site index of the stand. When related to stand density, top height enables the forester to estimate the expected yield for a specified future age (Coetzee 1994). Implicit in this concept are the assumptions that forests follow a predictable course of growth over time, determined by a single measure of site quality, and that specific relationships exist between stocking, height, diameter and volume (Battaglia and Sands 1998). According to Goulding (1994), the concept of site index may fail if silvicultural practices or environmental conditions are such that established growth relationships no longer apply. This failure may be even more evident for short-rotation tree crops since the measured site index could vary due to temporal changes in yield variation (Battaglia and Sands 1998). The definition of top height as used to determine site index in South Africa is calculated as the mean height of the 20% of the trees per hectare with the largest diameters at breast height (Bredenkamp 1993).

However, to assess if site index, as determined by top height, was affected by the different vegetation management treatments, the dominant 25% of the trees per treatment plot were compared to each other using height, diameter at breast height, volume, taper and mean, when using all the data. It must be noted that as each treatment plot consisted of 12 measured trees, it was not possible to determine the largest 20% of the trees. Instead, the dominant three trees per plot were used (25% of the trees per plot), the results of which are shown in Table 2.

Although significant differences were detected for all the variates when using the data for all the measured trees, no significant differences were detected for tree height, diameter at breast height and volume when using the top 25% of the performing trees. The difference between the tree heights for the manually weeded treatment and the non-weeded control was reduced from 15.66% to 6.49% with the use of the dominant trees. At present, there are no data available for the determination of top height for *Eucalyptus* hybrids grown in Zululand. However, based on available site index curves calculated by Coetzee (1994) for *Eucalyptus grandis* grown in KwaZulu-Natal, the manually weeded treatment would have had a site index of 16 when using the mean height of all the trees, and 17 when using top height. In contrast, the non-weeded control would have been assigned a site index of 14 if the mean height of all the trees was used, and 16 for top height. The rest of the treatments (except for the velvet bean cover-crop) would also have been assigned a site index of 17 with the use of top height.

Thus, in terms of predicting the potential of the yield of the site, the use of top height would give a satisfactory estimate, provided adequate weed control is carried out. If a compartment is left in an untended (no weed control) state, the ability to accurately predict the future volume of the trees with the use of top height alone would be difficult, due to the suppressed trees having a smaller diameter in relation to the height. This is evident by the 16.8% reduction in tree diameter at breast height, and the 32.6% reduction in volume per tree in the absence of any weed control, despite the use of only the top 25% of the trees. This height-to-diameter relationship (taper) still remains significant ($P < 0.023$), even with the use of only the top performing trees. The non-weeded control was the only treatment to have a significantly different taper from the manually weeded treatment. As treatment-induced mortality was not significant, the indications are that the established growth relationships, as required by site index, were only affected in the non-weeded control. As part of the standard weed control operations, some form of minimal weed control is implemented during the estab-lishment of commercial eucalypt plantations. This means that it will become increasingly unlikely that situations will arise where the lack of any weed control will affect the form of the trees. For com-partments where this does occur, special care will have to be taken such that the site-index model takes into account the actual rather than the predicted potential.

Weeding costs as a function of final yield

One month after the initial pre-plant spray, all the plots except for the non-weeded controls were weeded. In addition to this, three more manual weed control operations were carried out in all the treatments except for the cover-crops and chemically weeded treatment, each of which received only one further weeding (Table 3). In terms of the number of weed control events, the use of the cover-crops or herbicides for the control of competing vegetation was far more effective than manual hoeing. The herbicide used in this trial, glyphosate, is translocated to the actively growing regions of the weed, ensuring an effective kill. With manual hoeing, the weeds are often only topped, leaving the root system intact, while those that reproduce by vegetative means are able to regrow, albeit in a different position. In addition, continual topsoil disturbance through hoeing renders conditions more favourable for seed germination and seedling growth. Since chemical weeding results in all the weeds coming into contact with some herbicide, all the weeds are killed, whereas with manual hoeing, often smaller weeds are left.

To obtain an understanding of the costs per unit growth obtained, the price per hectare (US\$ ha^{-1}) was divided by the merchantable volume per hectare (m^3 ha^{-1}), yielding the amount spent in obtaining a m^3 of timber (Table 3). The two best-performing treatments, also with the largest areas kept manually weeded (manual weed free and no ring weeding treatments), cost the most, at approximately US\$4.4 m^{-3}. In terms of keeping the entire area free of weeds, the chemically weeded treatment was the most cost-effective, whilst the ring weeding and the non-weeded control were the least costly, albeit at the expense of reduced tree growth.

Table 4: Ranking of treatments in terms of timber volume output and weed control input costs in a weeding and cover-cropping trial situated in Zululand, South Africa

		Timber volume output		
		High	Medium	Low
	High	Manual weeding (US\$4.49 m^{-3})[1] No ring weeding (US\$2.16 m^{-3})	–	–
Weed control input costs	Medium	–	Row weeding (US\$1.97 m^{-3}) Inter-row weeding (US\$2.16 m^{-3})	Cowpea cover-crop (US\$3.14 m^{-3}) Velvet bean cover-crop (US\$3.10 m^{-3})
	Low	Chemical weeding (US\$1.25 m^{-3}) Ring weeding (US\$0.77 m^{-3})	–	Non-weeded control (US\$0.33 m^{-3})

[1] The figure enclosed in brackets is the total weed control costs incurred during establishment expressed as a function of merchantable volume (amount spent on weed control to obtain a m^3 of timber)

The profit to be gained from establishment weed control is affected both directly and indirectly by the method of weed control, while any improvement in yield needs to be taken into consideration together with any monetary input, in terms of weed control expenditure. For example, the manually weeded treatment not only had the highest merchantable volume of 223.9m^3 ha^{-1}, but also had the highest weed control input costs of US\$1 006 ha^{-1} (Table 3). In comparison, the chemically-weeded treatment produced 191.4m^3 ha^{-1}, at a cost of only US\$239 ha^{-1}. By taking the weed control costs into consideration, the profit difference between these two treatments was reduced from US\$678.9 ha^{-1} to US\$–88.1 ha^{-1}, indicating the importance of taking all factors into account.

In order to compare the different treatments, they were first ranked by timber volume and weed control costs. The treatments were then further separated into low, medium and high classes (Table 4). Provided long-term sustainability is not jeopardised, the ideal scenario in terms of any form of silvicultural management is to obtain maximum return for minimum cost. Higher input costs will need to be justified, in terms of significant growth benefits and profit, before they can be considered a viable option. If this were not the case, or where significantly improved growth could not be guaranteed, there would be an increased risk associated with carrying higher weed control costs over a full rotation. Although the manually weeded treatment produced the second highest returns (after weed control input costs were deducted), it was not significantly different from the row, no ring, chemically and ring weeded treatments. This places it in the high-risk category, as the high weed control input costs could not be statistically guaranteed to result in improved yield.

The chemically and ring weeded treatments are examples of low input/high output treatments. Although the volume obtained from these treatments was not as high as the manually weeded treatment, the lower cost of applying herbicides and the small area that was manually ring-weeded contributed to a higher profit. These low input costs also carry a lower risk, as shown by the amount of money spent to obtain 1m^3 of timber (Table 4). If the size of the ring weeding is to be increased, then the additional costs of this operation need to be justified, in terms of profit obtainable from a significantly improved volume.

The competitive nature of the cover-crops when planted at the same time as the trees resulted in a low timber volume output. If these cover-crops could be planted in such a manner so as to minimise tree suppression and maximise weed suppression, a medium input/high output scenario could be achieved.

The no ring and inter-row weeding treatments should not normally be considered as a viable option, due to the high risk of mortality associated with the retention of weeds in the immediate vicinity of the tree when small. Although mortality was not significant in this trial and resulted in higher than expected timber volumes, there is a considerable body of evidence to suggest that these are high-risk treatments.

The non-weeded control is in the low weed control input/low volume output class, confirming that, on this site, some form of vegetation management would be needed, due to the severity of weed competition.

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